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# SOME CHARACTERISTICS OF TUNGSTEN FILAMENTS OPERATED AS CATHODES IN A GAS DISCHARGE

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SOME CHARACTERISTICS OF TUNGSTEN FILAMENTS OPERATED AS CATHODES IN A GAS DISCHARGE

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ABSTRACT

Some physical properties of tungsten filaments, when operated as cathodes in a gas discharge, are presented. For 0.1524-cm-diam tungsten wire, the initiation of a discharge is found to be dependent on the filament geometry. The effect of connecting the discharge power supply to either the positive or negative leg of the filament is examined. When the emission current becomes a sizable fraction of the filament heater current, the filament does not emit uniformly. The temperature distribution indicates that the majority of the electrons are emitted from the negative leg of the filament.

# INTRODUCTION

Tungsten filaments have been widely used in lighting, electronic tubes, and as electron emitters for ion or plasma sources. Tungsten is chosen as a thermal electron emitter because of its very high melting point (3683°K). When heated to a temperature of 2370°K or more, tungsten is a copious emitter of electrons and requires no activation. A tungsten wire is generally directly heated by passing a current through it. The emitted electron current density, $J_e$, is limited by space charge. For high extraction electric fields, a saturation current density, $J_{max}$, is reached, which is approximately given by the Richardson-Dushman equation:

$$J_{max} = A_o T^2 \exp\left(-\frac{e\phi}{kT}\right) \qquad (1)$$

where $A_o$ is Dushman's constant ($1.2 \times 10^6$ A/m$^2$-deg$^2$), T is the filament temperature in degrees Kelvin, e is the electron charge, $\phi$ is the work function in volts, and k is the Boltzmann constant. It can be seen that $J_{max}$ depends very strongly on the filament temperature. If saturation does not occur, the current density will depend on the extraction voltage. If a filament wire and an anode form a cylindrical diode with radius $r_f$ and $r_a$ respectively, the current density, $J_e$, at the anode is given by the well-known Child's Law:

$$J_e = 4/9\ \varepsilon_o (2e/m)^{1/2}\ V^{3/2}\ r_a^{-2}\ \beta^{-2} \qquad (2)$$

where $\varepsilon_o$ is the permittivity of free space, m is the mass of the electron, V is the applied potential, and $\beta$ is a correction coefficient, which is a function of $r_f/r_a$.[1] If for a given filament temperature, the extracted electron current density, $J_e$, obeys Eq. (2) the filament is said to be operated in the space-charge limited region. Otherwise it is said to be operated in the emission limited region.

In the presence of a low-pressure discharge plasma, a hot filament always has a double sheath surrounding it. The plasma at the sheath edge now becomes the "anode" surface. Within the sheath region, the total current is made up of a beam of thermionically emitted electrons, which are accelerated towards the plasma boundary, and a flow of positive ions, which are accelerated from the plasma back into the filament. Electrons from the plasma may penetrate the sheath region but if their energy is less than the sheath potential, they will be reflected back into the plasma. The double sheath in a planar geometry has been analyzed by a number of authors.[2-4] Under space-charge limited conditions, i.e., with zero electric field at the cathode surface, it has been shown that the ratio of the emitted electron density to the ion current density $J_e/J_i = \alpha(M/m)^{1/2}$ where M is the ion mass, $J_i$ the ion current density, and $\alpha \approx 0.4$.[3,4] The number of electrons that can be extracted from a hot filament is proportional to $J_i$, which is a function of the plasma density, n; the plasma electron temperature, $T_e$; and the extraction voltage, V.[3,4]

In Section I of this paper, some physical properties of tungsten filament are presented. Section II describes the discharge characteristics of the large- and small-size filaments. Section III compares the two different ways of biasing a filament in a DC discharge.

## I. THEORETICAL CONSIDERATIONS

When a tungsten filament is used as a thermal electron emitter, it is important to know the relationships among the filament diameter, heater current, filament temperature, emission current, and lifetime. The specific characteristics of an ideal tungsten filament have been studied extensively by Jones and Langmuir.[5] From the published data, the heater current as a function of filament temperature has been calculated for filament diameters, d, from 0.0254 cm to 0.1524 cm (see Fig. 1). For a given filament temperature, the required heater current goes up as $d^{3/2}$. Figure 2 shows a plot of electron emission current per cm of length of wire versus filament temperature for different diameters of filaments. For a given filament temperature, the electron emission increases linearly with the diameter. The lifetime of a tungsten filament is generally defined as the time required to evaporate away 10% of the original diameter. The evaporation rate is a function of filament temperature.[5] For a given filament temperature and length, the volume goes up as $d^2$ but the surface area increases as d. Consequently the filament lifetime increases linearly with d.

Once an electron is emitted from the filament, it will be attracted to the anode by the electric field. However, because of the heater current, a magnetic field, B, is always produced. Depending on the magnitude of the heater current, this B-field can be quite strong. Figure 3 shows the calculated B-field on the filament surface as a function of heater current for different filament diameters. The electric and magnetic fields are normal to each other on the filament surface. Under these conditions, the emitted electron's motion will be cycloidal with the guiding center drifting along the filament (the E x B drift) in a direction as shown in Fig. 4. The velocity for this type of drift is given by $v_d = 10^8$ E/B, where E is measured in volts/cm, B in gauss, and $v_d$ in cm/sec.[6]

In addition to the E x B drift, there is a drift that is caused by a variation in the magnetic field. The gradient in B in the radial direction causes the Larmor radius to be larger at the top of the orbit than at the bottom, and this leads to the grad-B drift.[6] The direction of this drift is perpenditular to both B and grad B and for the electron it is in the same direction as the E x B drift. In most cases, the E x B drift velocity is larger than that of the grad-B drift. The effect of these drifts will cause the emitted electron to move parallel to the filament until it comes to a point where the filament changes its curvature. The momentum will then carry the electron away from the filament. In the case of high neutral pressure, the electron may also be scattered away from the filament by collisions with neutral particles.

In some situations where the B field on the filament surface is strong, the amplitude of the cycloidal path will be very small. The electron returns to the filament surface once every cyclotron period. However, in the case where the B-field is weak (as in the case of a small-diameter filament), the amplitude and the horizontal distance transversed in a cyclotron period will be large, and the electron may escape from the filament (Fig. 5). The trajectory of a 50-eV electron has been analyzed and the amplitude or turning radius, $R_m$, has been determined for four different filament diameters with the assumption that all are operated at a temperature of 3000°K. Table I gives a summary of the result. It can be seen that for the same filament temperature, a 50-eV electron has a much larger turning radius for a 0.0381-cm-diam wire than a 0.1524-cm-diam wire.

## II. FILAMENT DISCHARGE TESTING

The discharge characteristics of tungsten filaments have been studied in a cylindrical copper chamber (11.4-cm diam by 22.8-cm long) in the presence of hydrogen gas. A straight tungsten wire, 0.1524 cm in diameter and 10 cm long was laid along the axis of the chamber and supported loosely at two ends by copper rods as shown in Fig. 6(A). The filament was biased at -70 V with respect to the chamber wall. With a heater current of 90 A, and a temperature of about 2500°K, approximately 1.45 A of electron emission current should be available. However, no discharge could be obtained for neutral pressures below $10^{-2}$ Torr. The same result was found even when there was a pre-existing hydrogen plasma. (The plasma was produced by a small 0.01-cm-diam filament and the density was $\approx 10^9$ ions/cc.) At a neutral pressure of $10^{-2}$ Torr, the mean free path of the electron is approximately 14 cm in a hydrogen gas. If this path length exceeds the filament length, the probability of an electron being scattered away by collision is small and no discharge can be developed. The thermal electrons will just drift along the filament surface until they reach the filament holder. However, if the filament heater current, $I_f$, is turned off, the B-field will diminish immediately. The filament, however, is still hot enough to emit electrons, which can now go directly to the chamber wall. The oscilloscope traces of Fig. 7(A and B) show the discharge current, $I_d$, as a function of time with and without pre-existing plasma, respectively, after $I_f$ was switched off. The decay of $I_d$ is due to the cooling of the filament. If during the decay, $I_f$ is switched on again, $I_d$ is seen to drop immediately to zero as shown in Fig. 7(C). In other words, with a straight large-diameter, directly heated filament, the magnetic field that surrounds the filament can be sufficient to prevent the discharge from operating (for the above case $R_m \approx 3$ mm).

Figure 6(B) shows a picture of a tungsten wire of the same diameter and length except that it is bent to form a hairpin filament. The heater current, $I_f$, was 90 A and the discharge voltage was 70 V. This time the discharge took place even at pressures in the range of $10^{-4}$ Torr. In this configuration electrons can leave the filament at the corners and a discharge is formed. Figure 7(D) shows the discharge current, $I_d$, as $I_f$ is turned off. A discharge can similarly be obtained from a linear but bumpy filament.

In the Berkeley 24-cm x 24-cm multi-line-cusp ion source,[7] 0.1524-cm-diam tungsten wire is used as the cathode. Each filament has several bends, as shown in Fig. 8. This arrangement will enable the electrons to leave the filament after drifting a short distance. It also helps to reduce the loss of thermal emitted electrons to the positive filament holder.

Tungsten filaments of 0.0508-cm diam were also tested in the same test chamber. It was found that a 5-cm-long straight wire could produce a discharge at neutral pressure as low as $10^{-4}$ Torr. In this case, the amplitude of the cycloidal path for the emitted electron is approximately 2.5 cm. The horizontal distance traversed by the electron in a cyclotron period is longer than 12 cm, which is more than twice the filament length. The electron will completely miss the filament and travel directly to the chamber wall. Figure 9(A) shows the discharge current, $I_d$, as a function of time for the straight filament after $I_f$

is cut off. $I_d$ is found to remain constant for approximatley 200 ms. During this period of time, the filament is operated in the space-charge limited condition. An abundance of electrons is available but $I_d$ is limited by the plasma density, n; plasma electron temperature, $T_e$; and the discharge voltage, $V_d$. As the temperature of the filament drops to a value where emission-limited regime is reached, $I_d$ starts to decrease. Figure 9(B) shows $I_d$ as a function of time for a 20-cm-long hairpin filament after $I_f$ is cut off. For the top trace, the initial value of $I_f$ is 24 A and for the bottom trace 20 A. It can be seen that the time for the filament to reach the emission-limited regime is shorter when $I_f$ = 20 A. Because $I_d$ is insensitive to variations in $I_f$ when the emission is space-charge limited, it is generally favorable to operate the filament in this regime.

## III. FILAMENT BIAS CONNECTION

In a plasma generator, a hot tungsten filament heated by direct current is often used as the source of energetic electrons. There are two ways of connecting the discharge power supply to the filament. In the circuit arrangement of Fig. 10(a), the negative terminal of the discharge power supply is connected to the positive terminal of the dc filament heater supply. In Fig. 10(b) the negative terminals of the two supplies are connected together. In order to investigate the difference between these two electrical connections, the currents passing through the positive and negative legs of a 10-cm-long, 0.508-mm-diam hairpin tungsten filament were recorded when the discharge was switched on and off. Tables II and III summarize the results of the measurements.

In the arrangement of Fig. 10(a), 20.45A of filament heater current passed through the filament and through meters A and B when the discharge was turned off. When the discharge current, $I_d$, was 1.62 A, the reading of meter A increased to 21.5 A but the reading of meter B decreased to 19.9 A.

The filament heater supply used in this measurement was a constant-voltage supply. When the discharge was turned on, the additional 1.62 A of discharge current should increase the temperature and therefore the resistance of the filament, resulting in a drop of the filament heater current, $I_f$. The current through meter A exceeded that of meter B by 1.60 A, which is equal to $I_d$. Thus in this arrangement the discharge current, $I_d$, is not emitted from the positive leg of the filament but passes through the filament heater supply and then is emitted from the negative leg. Only the filament heater current, $I_f$, passes through the positive leg.

In the arrangement of Fig. 10(b), the current readings of meters A and B (Table III) show that the discharge current, $I_d$, does not go through the filament heater supply. The current through B is greater than that of A by an amount equal to the discharge current.

The fact that $I_d$ passes through the negative leg of the filament in both the circuit connections discussed can be visually observed from the variation of the light emission intensity of the filament. Photographs of the light emitted from a filament, taken with cross-polaroid filters, are shown in Fig. 11. Fig. 11(A) is a photograph of a 0.5-mm-diam filament, which has been heated to about 3370°K. As can be seen, the filament is heated rather uniformly, except near the ends where the heat is conducted away to the water-cooled filament mounts. Fig. 11(B) is a photograph of the same filament with a discharge operating. In this case, the discharge current, $I_d$, emitted by the filament is over half the heater current. The negative leg of the filament is clearly much hotter than the remainder of the filament. The majority of the electrons are emitted from the very hot negative leg, hence the positive leg is heated only by the reduced heater current, as described in Table II, and so becomes cooler. The peak temperature of the negative leg of the filament is related to the ratio of $I_d/I_f$ and the filament's lifetime will be limited by a burn-out somewhere along the negative leg.

A thin tungsten filament ($\sim$0.127-mm diam) is an obvious choice when only a small discharge current is needed because a smaller $I_f$ is required to heat the filament. In that respect, the circuit can be connected as shown in Fig. 10(a). A small-diameter filament requires a higher heater voltage, which is added to that of the discharge supply. If $V_d$ is the discharge voltage and $V_f$ the heater voltage, electrons emitted from the filament will possess energy ranging from $V_d$ to $(V_d + V_f)$. On the other hand, if the filament is connected as in Fig. 10(b), the electron energy will vary from $(V_d - V_f)$ to $V_d$. In many cases, available laboratory power supplies are limited in voltage. Thus by connecting the filament as shown in Fig. 10(a), an additional discharge voltage equal to the heater voltage can be obtained.

However, when hundreds of amperes of discharge current are required, thicker tungsten filaments can be used. The filaments would then be connected as shown in Fig. 10(b) so that $I_d$ will not pass through the filament heater supply to generate additional load.

ACKNOWLEDGMENTS

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REFERENCES

1. I. Langmuir and K. B. Blodgett, Phys. Rev. 22, 347 (1923).
2. I. Langmuir, Phys. Rev. 33, 954 (1929).
3. F. W. Crawford and A. B. Cannara, J. Appl. Phys. 36, 3135 (1965).
4. P. D. Prewett and J. E. Allen, Proc. R. Soc. London A, 348, 435 (1976).
5. H. A. Jones and I. Langmuir, Gen. Elec. Rev., 30, 310 (1927).
6. F. F. Chen, Introduction to Plasma Physics (Plenum Press, New York, 1974).
7. K. W. Ehlers and K. N. Leung, Bull. Am. Phys. Soc., 23, 805 (1978).

TABLE I. Turning radius ($R_m$) for four tungsten filaments of different diameters (operated at 3000°K).

| Wire diameter (cm) | Heater current (A) | $R_m$ (cm) |
|---|---|---|
| 0.0381 | 16.25 | 28.4 |
| 0.0508 | 25.04 | 2.92 |
| 0.1016 | 70.80 | 0.254 |
| 0.1524 | 130.0 | 0.189 |

TABLE II. Meter readings for circuit shown in Fig. 10(a).

| Discharge | Meter readings (amperes) | | | |
|---|---|---|---|---|
| | A | B | C | A − B |
| on | 21.5 | 19.9 | 1.62 | 1.60 |
| off | 20.45 | 20.45 | 0 | 0 |

TABLE III. Meter readings for circuit shown in Fig. 10(b).

| Discharge | Meter readings (amperes) | | | |
|---|---|---|---|---|
| | A | B | C | B − A |
| on | 21.5 | 23.5 | 1.95 | 2.0 |
| off | 22.2 | 22.2 | 0 | 0 |

## FIGURE CAPTIONS

Fig. 1. Filament heater current as a function of filament temperature for different diameters of tungsten wire.

Fig. 2. Electron emission current per cm of length as a function of filament temperature for different diameters of tungsten wire.

Fig. 3. The magnetic field at the filament surface as a function of filament current for different diameters of tungsten wire.

Fig. 4. A hairpin tungsten filament showing the direction of the E x B drift for the electrons.

Fig. 5. The trajectory of an electron emitted from the filament surface.

Fig. 6. The experimental set-up for a straight and a hairpin tungsten filament.

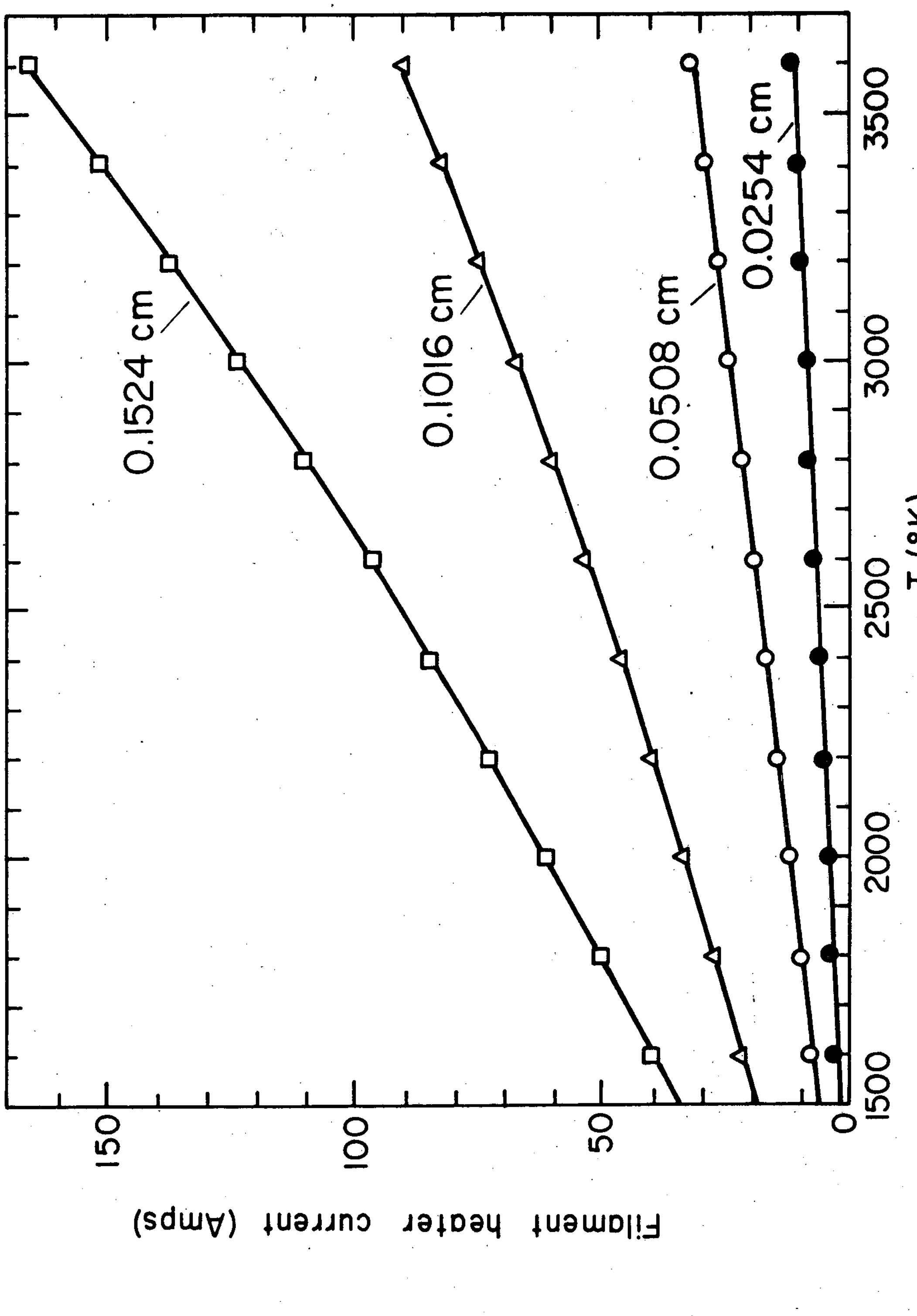
Fig. 7. Discharge current from a 0.1524-cm-diameter tungsten filament as a function of time after the filament heater power supply is switched off.

Fig. 8. Filament arrangement of the Berkeley 24-cm x 24-cm multi-line-cusp ion source.

Fig. 9. Discharge current from a 0.0508-cm-diameter tungsten filament as a function of time after the filament heater power supply is switched off.

Fig. 10. The two circuit arrangements for biasing a DC heated filament in a gas discharge.

Fig. 11. Photographs of a hairpin filament taken through cross polaroid filters (A) without, and (B) with discharge current.




XBL788-1658

Figure 1

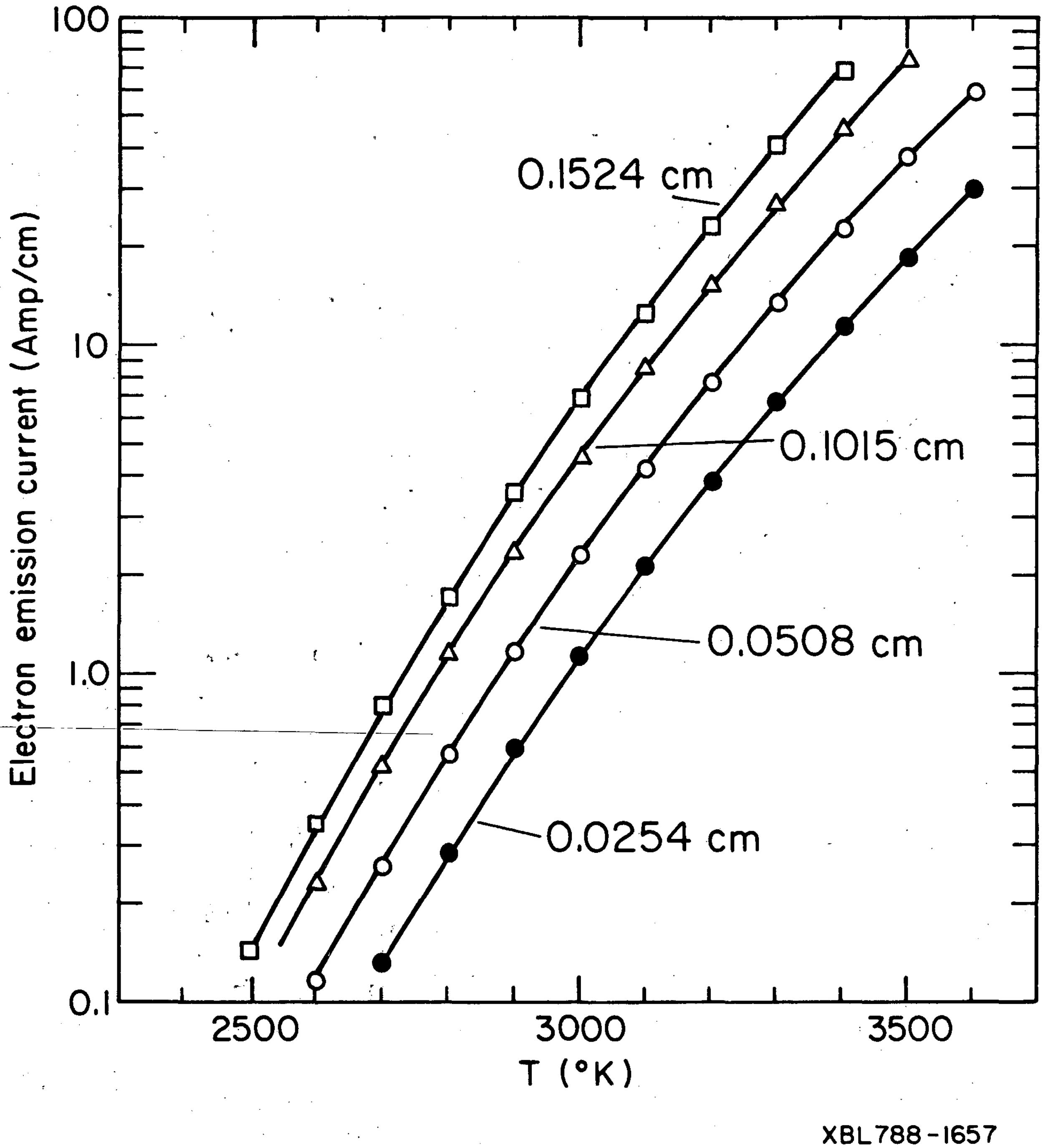

100
10
1.0
0.1
Electron emission current (Amp/cm)
2500
3000
3500
T (°K)
0.1524 cm
0.1015 cm
0.0508 cm
0.0254 cm
XBL788-1657

Figure 2

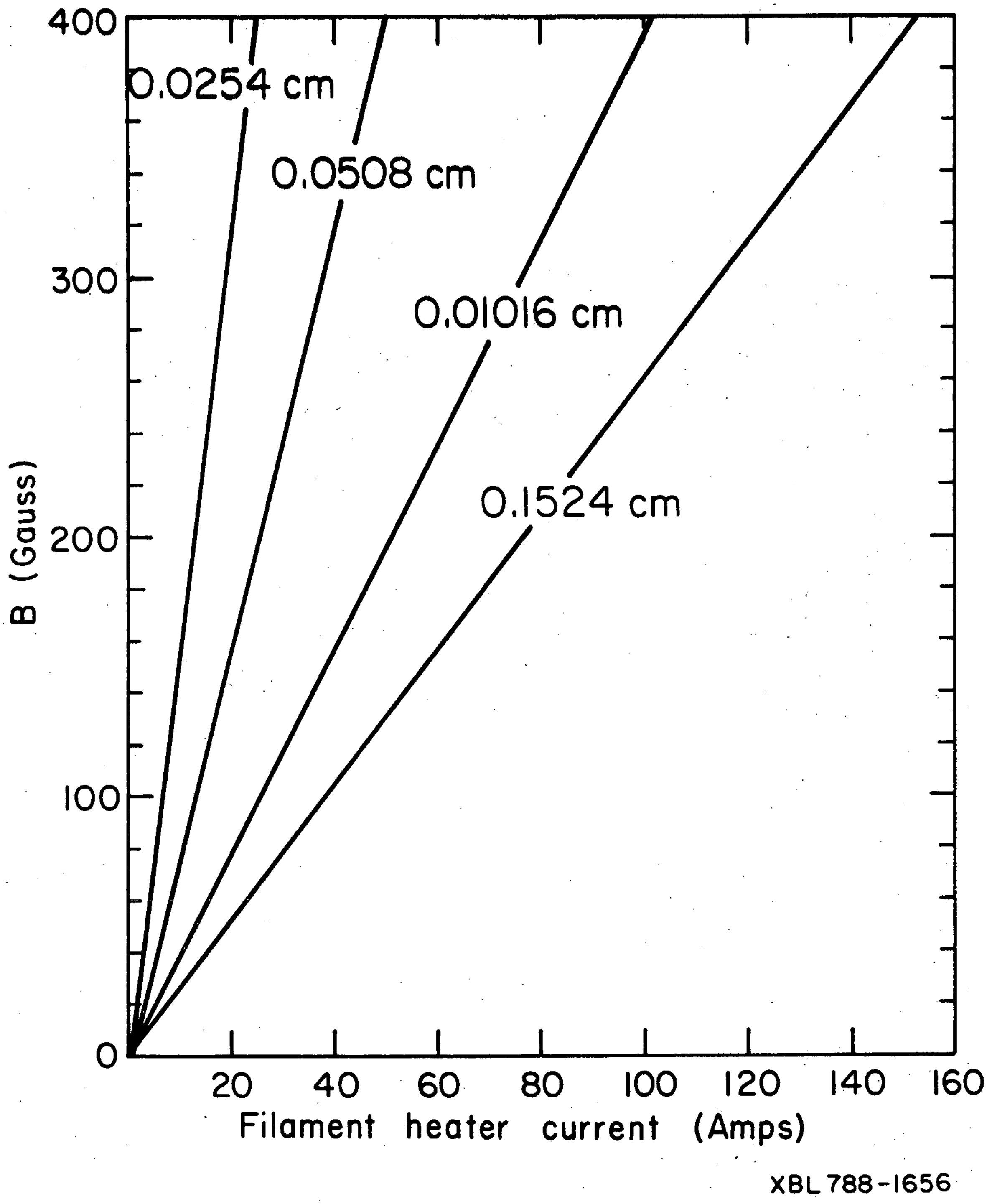
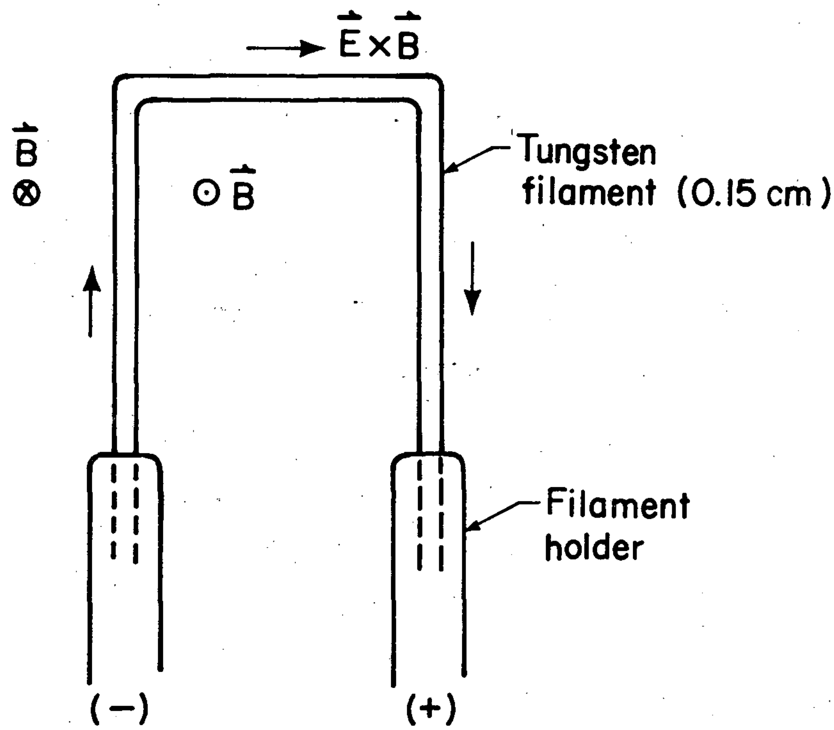

400
300
200
100
0
B (Gauss)
0.0254 cm
0.0508 cm
0.01016 cm
0.1524 cm
20
40
60
80
100
120
140
160
Filament heater current (Amps)
XBL 788-1656

Figure 3




XBL 788-2617

Figure 4

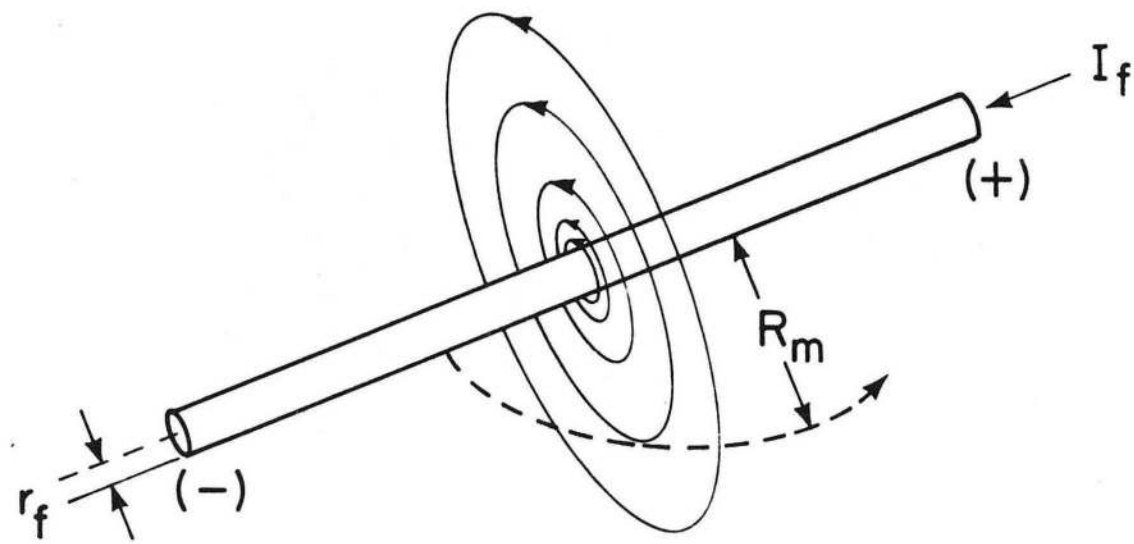



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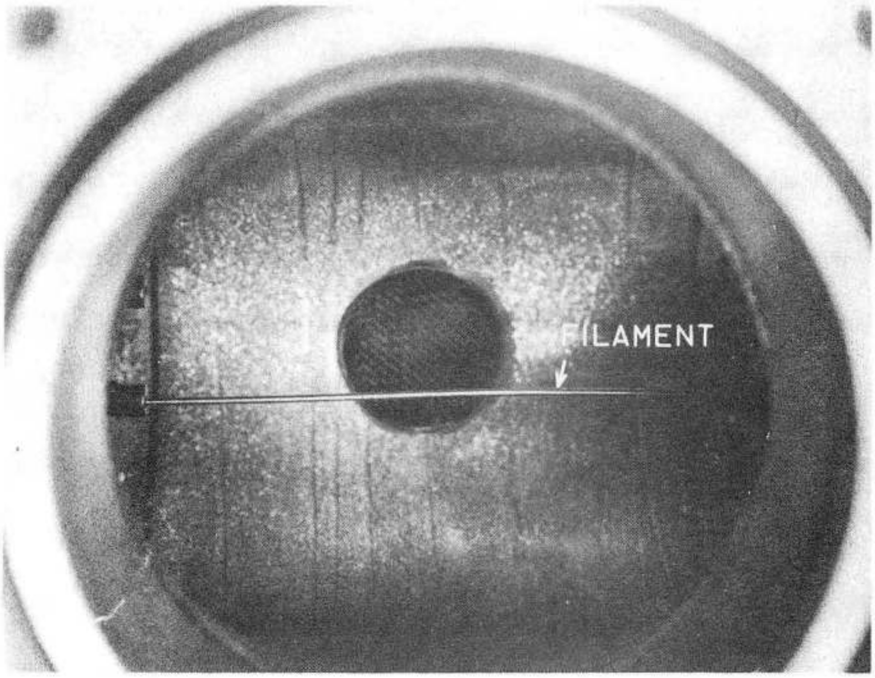
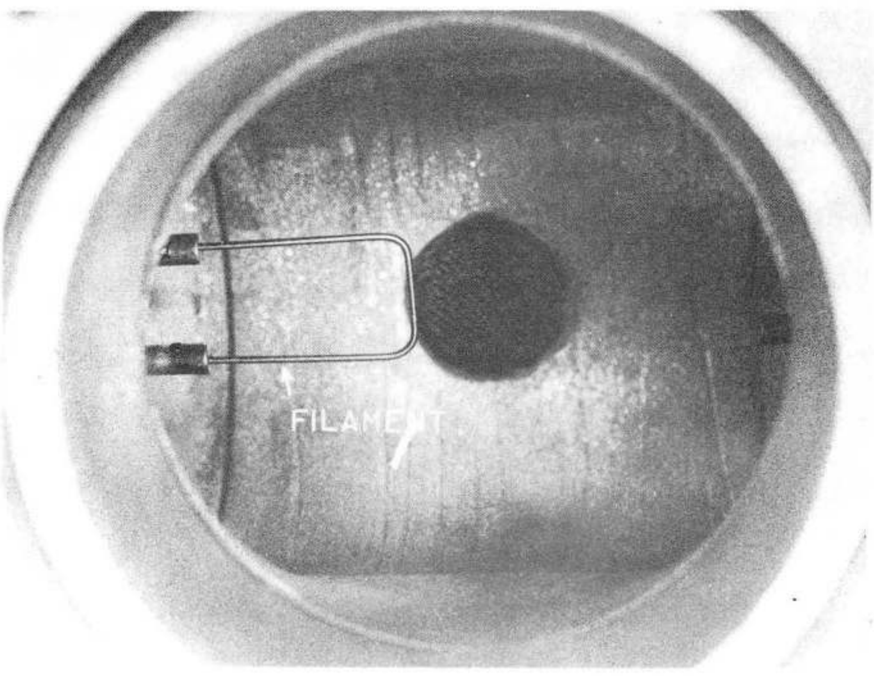
Figure 5




(A)




(B)

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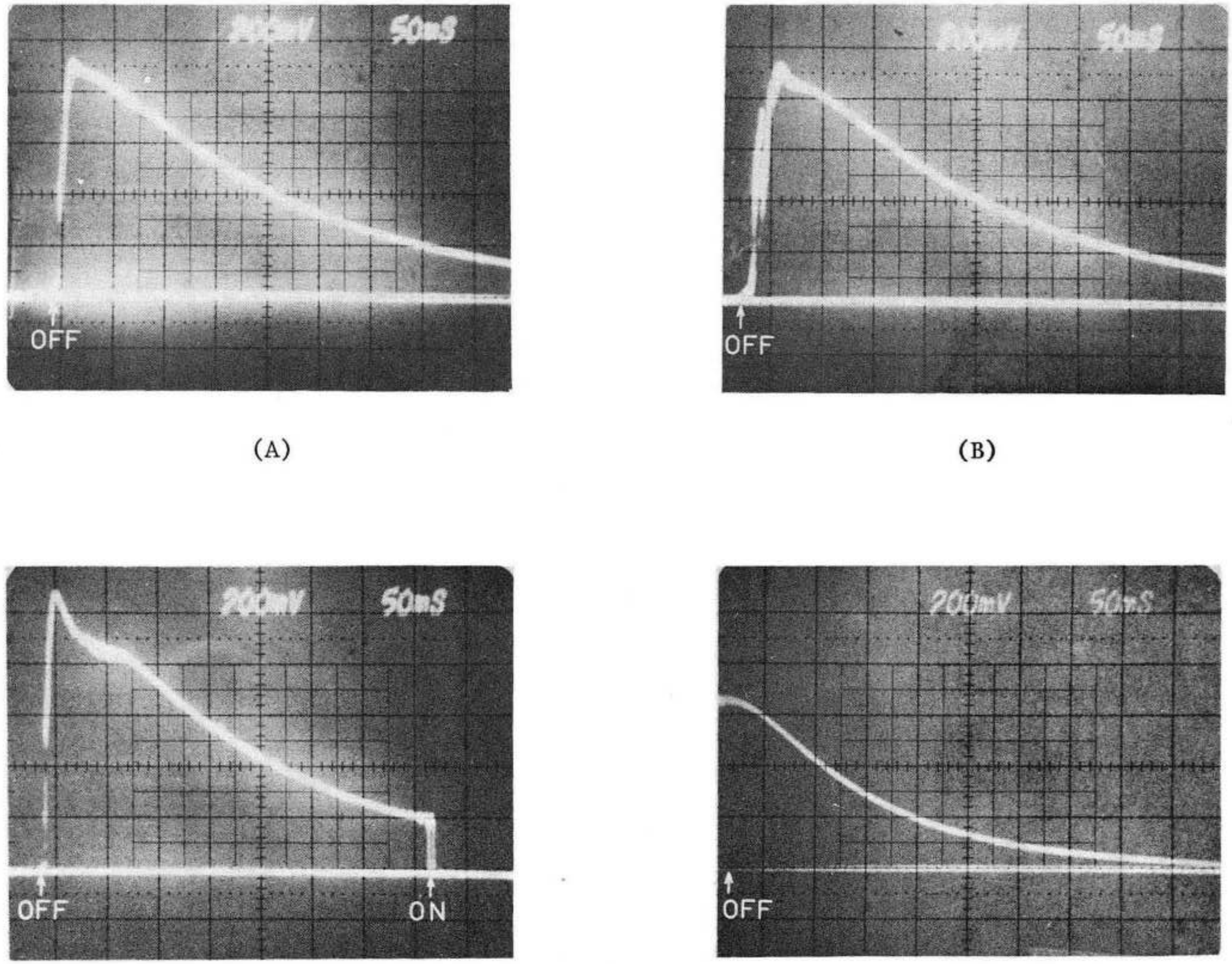
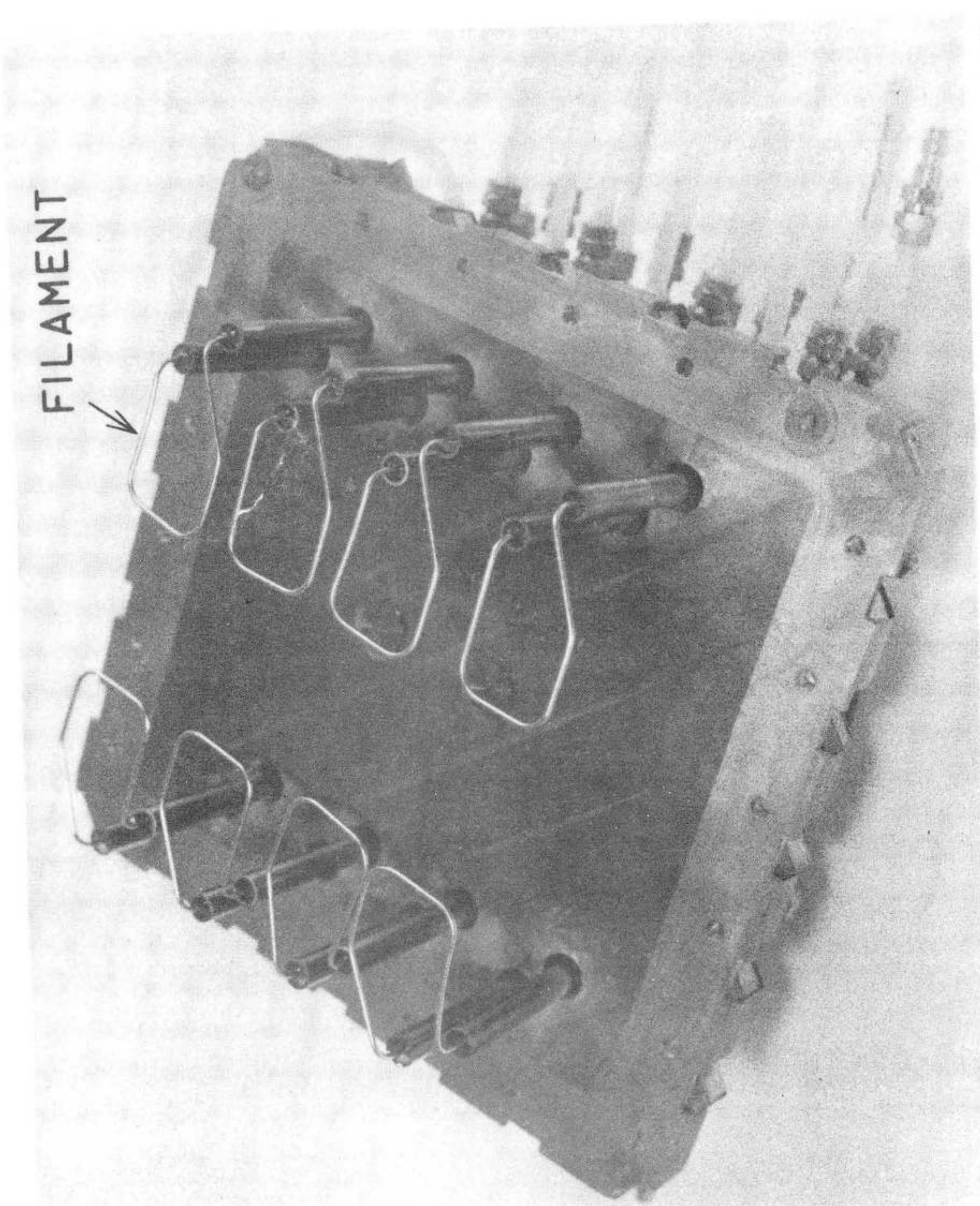
Figure 6




(A) (B) (C) (D)

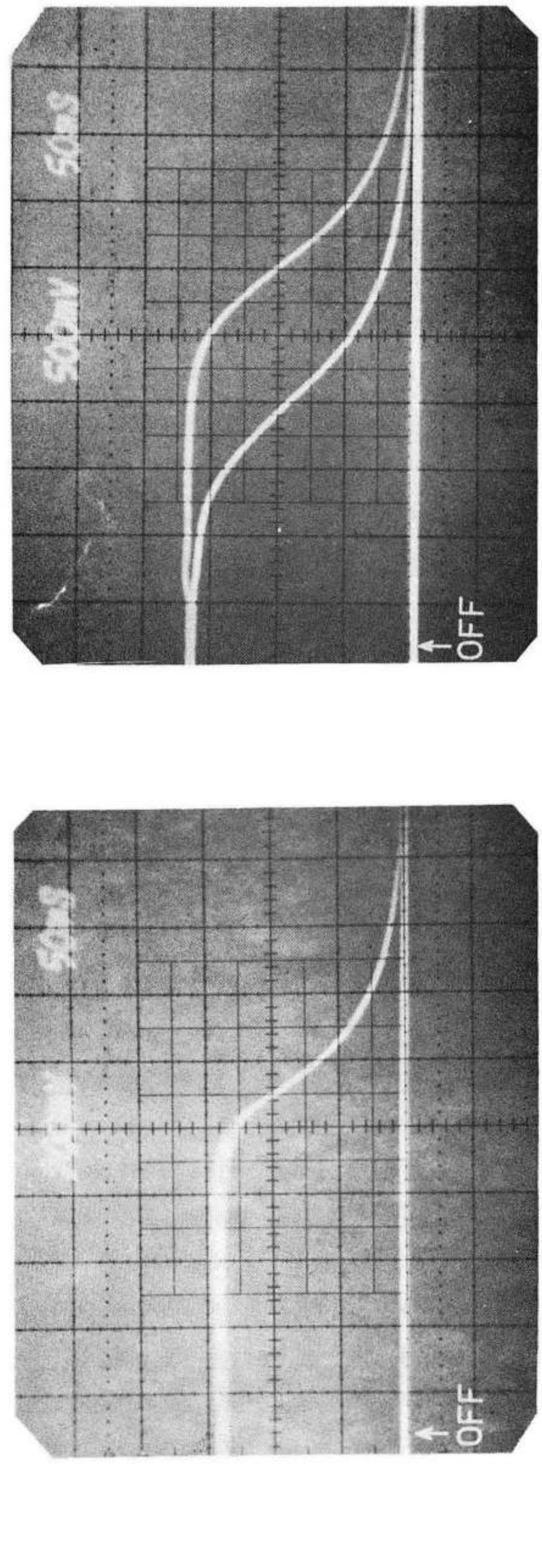
XBB 788 10415

Figure 7




XBB 788-10411

Figure 8




(A) (B)

Figure 9

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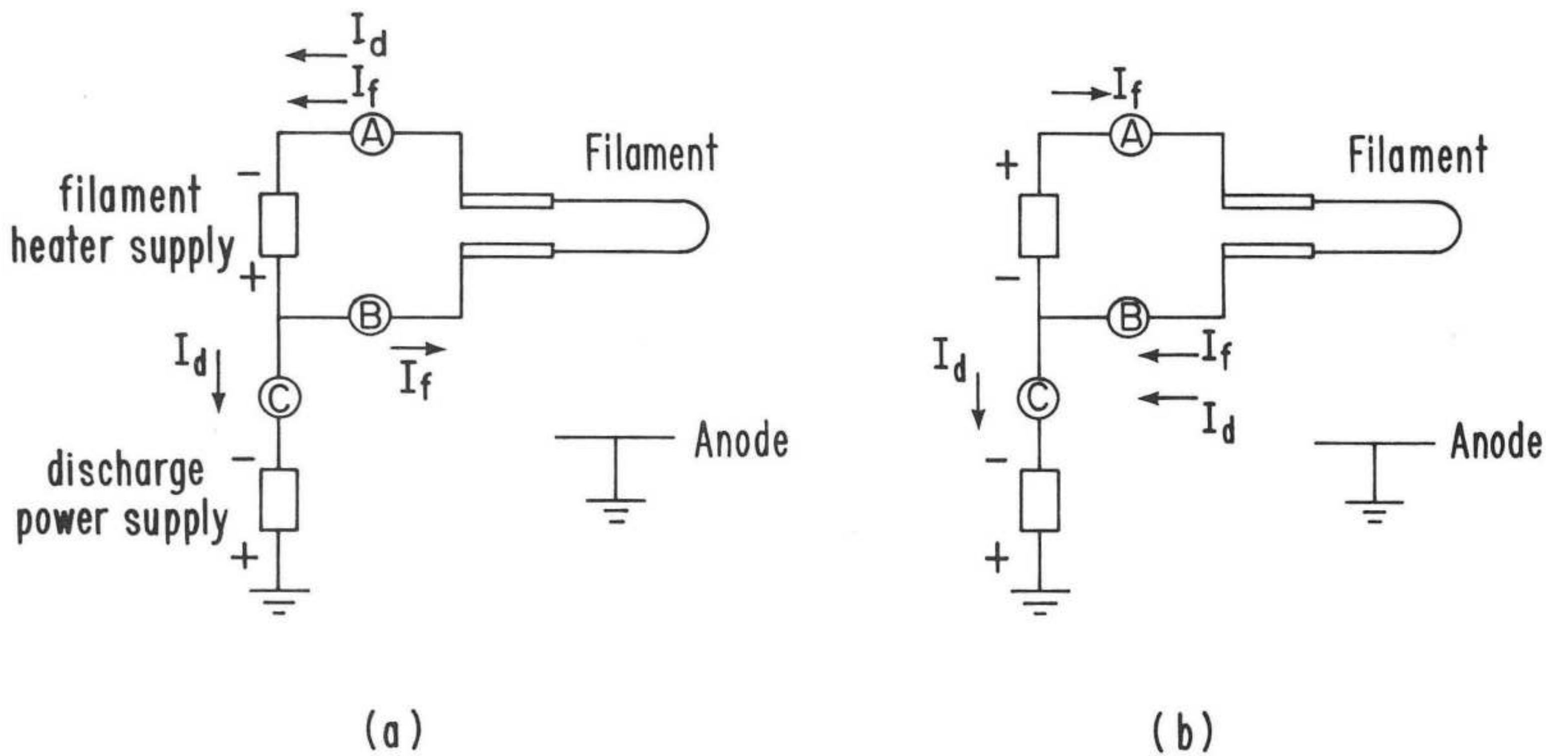
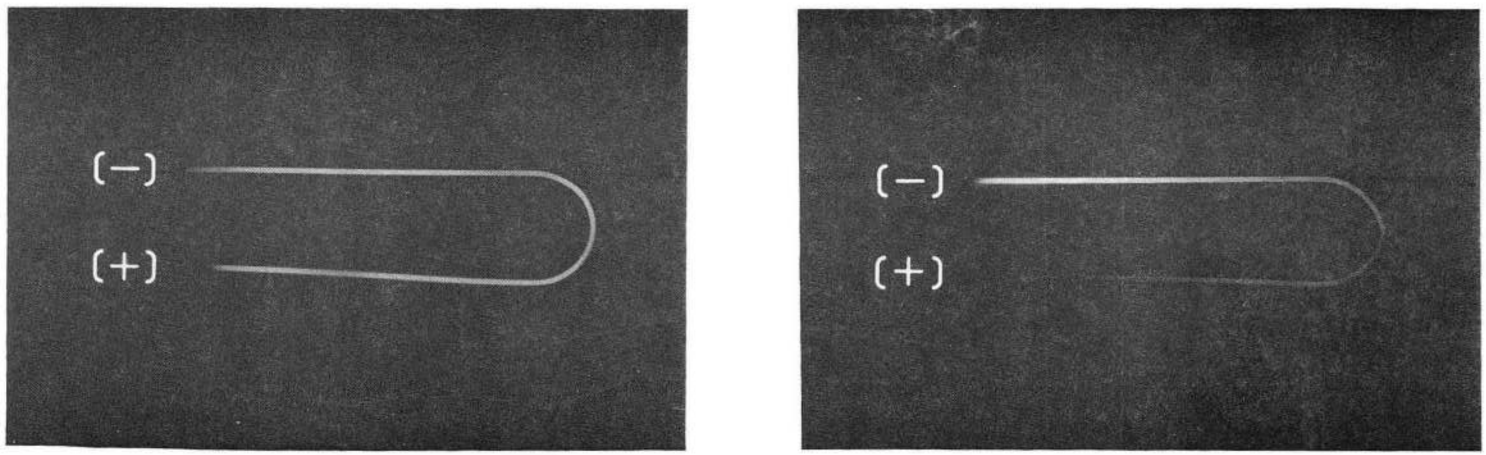



XBL 788-1655

Figure 10




(A) (B)

XBB 788 10413

Figure 11

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